**COSMOGENIC NUCLIDES AND NOBLE GAS EVIDENCE THAT ALMAHATA SITTA CHONDRITES REPRESENT FRAGMENTS OF ASTEROID 2008 TC3**. K. C. Welten[1], M. M. M. Meier[2], M. W. Caffee[3], K. Nishiizumi[1], R. Wieler[2], P. Jenniskens[4], M. H. Shaddad[5], [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA (kcwelten@ssl.berkeley.edu), [2]Department of Earth Sciences, ETH Zürich, CH-8092 Zürich, Switzerland, [3]Department of Physics, Purdue University, West Lafayette, IN 47907, USA. [4]SETI Institute, Carl Sagan Center, 515 North Whisman Road, Mountain View, CA 94043, USA. [5]Department of Physics, University of Khartoum, P.O. Box 321, Khartoum 11115, Sudan.

**Introduction:** On October 7, 2008, a small asteroid, 2008 $TC_3$, exploded in the atmosphere at an altitude of 37 km above the Nubian Desert of northern Sudan. Search expeditions yielded 600 meteorite fragments with a total mass of ~10.5 kg. Although the majority of the meteorites, known as Almahata Sitta, were classified as polymict ureilites [1], many non-ureilites were identified within the strewnfield [2-5]. These non-ureilites have also been attributed to the Almahata Sitta fall, based on their fresh appearance, their similar mass distribution within the strewnfield [3] and the presence of short-lived cosmogenic radionuclides in two of the samples [2]. It is not clear, however, how these chondrites relate to the Almahata Sitta ureilites, i.e., how and when they were incorporated into the ureilitic parent body. Previous work yielded a CRE age of ~20 Myr for the Almahata Sitta ureilites, which were part of a 3-4 m large object [6]. In this work, we measured the concentrations of the cosmogenic radionuclides $^{10}$Be ($T_{1/2}$ = 1.36 Myr), $^{26}$Al (0.705 Myr) and $^{36}$Cl (0.301 Myr), as well as light noble gases in two ordinary chondrites from the Almahata Sitta strewnfield to verify they are from the same fall and to study the CRE and thermal history of the chondrites in relation to the ureilitic samples of asteroid 2008 $TC_3$.

**Experimental and Results:** We received small chips of Almahata Sitta #25 (H5 chondrite, 222 g) and A100 (L4 chondrite, 11.4 g). After splitting off 0.23-0.25 g for noble gas analysis, we crushed the remaining sample and separated the metal and stone fraction for radionuclide analysis. The bulk metal contents of 18.2 wt% for #25 and 7.6 wt% for A100, as well as the chemical composition of the metal (Table 1) are consistent with their classification as H and L chondrites, respectively.

*Cosmogenic Radionuclides*. We dissolved 40-80 mg of purified metal, along with Be, Al and Cl carrier in dilute $HNO_3$ and ~130 mg of stone fraction, in the presence of Be and Cl carrier, in concentrated $HF/HNO_3$. After dissolution, we took a small aliquot for chemical analysis, and separated Be, Al and Cl using procedures described previously [6]. AMS measurements of $^{10}$Be, $^{26}$Al and $^{36}$Cl were performed at PRIME Lab, Purdue University. Normalized results [7-9] are given in Table 1.

*Noble gases*. Sample #25 (251 mg) and A100 (228 mg) were each divided into two subsamples of similar size, which were wrapped in aluminum foil and preheated in vacuum at 130 °C for ~24 hours to remove atmospheric gases. The samples were then heated to 1800 °C for ~30 minutes to extract and analyze He, Ne and Ar, following procedures described previously [10]. Results are given in Table 2. We assume that $^3$He is entirely cosmogenic, while $^4$He is mainly radiogenic with a small cosmogenic component with $(^4He/^3He)_c$ = 6. The measured $^{20}Ne/^{22}Ne$ ratios of 0.84-0.86 indicate that Ne is almost entirely cosmogenic, while the $^{36}Ar/^{38}Ar$ ratios of 3.3-4.3 indicate significant amounts of trapped Ar. We assume $^{36}Ar/^{38}Ar$ ratios of 0.65 for cosmogenic Ar and 5.32 for trapped Ar.

*Pre-atmospheric size*. The measured $^{10}$Be concentrations in the stone and metal phase of #25 and A100 indicate a pre-atmospheric size of ~300 g/cm$^2$, very similar to that of the Almahata Sitta ureilites [6]. The concentrations of cosmogenic $^{10}$Be, $^{26}$Al and $^{36}$Cl in the metal phase of #25 are ~30% lower than in A100, indicating higher shielding for Almahata #25. Based on calculated $^{10}$Be depth profiles for an object with a radius of ~300 g cm$^{-2}$, we derive shielding depths of 100-150 g cm$^{-2}$ for #25 and 30-50 g cm$^{-2}$ for A100 respectively. Both samples show small contributions (2-4 dpm/kg) of neutron-capture $^{36}$Cl in the stone fraction. These contributions are a factor of 2-4 smaller than expected for chondrites with a pre-atmospheric radius of 300 g cm$^{-2}$, which may indicate low native Cl contents of the Almahata chondrites.

*CRE age*. The low $^{22}Ne/^{21}Ne$ and $^3He/^{21}Ne$ ratios in the two chondrite samples confirm high shielding conditions and indicate that Almahata #25 was more heavily shielded than A100. The $^3He/^{21}Ne$ ratios of 3.55 and 3.85 fall consistently ~15-20% below the "Bern-line", suggesting loss of cosmogenic $^3$He. Assuming $^3$He, $^{21}$Ne and $^{38}$Ar production rates as a function of the $^{22}Ne/^{21}Ne$ ratio [11], the cosmogenic $^3$He, $^{21}$Ne and $^{38}$Ar concentrations yield average CRE ages of 19±3 Myr for #25 and 23±4 Myr for A100, with the $^3$He ages being consistently lower and the $^{38}$Ar ages consistently higher than the $^{21}$Ne ages.

We also used elemental production rates of [12] to calculate the $^{21}Ne/^{26}Al$ ages for #25 and A100, as we did for the ureilites [6]. The measured $^{21}Ne/^{26}Al$

ratios in #25 and A100 yield shielding-corrected CRE ages of 21 and 23 Myr, which are almost identical to the $^{21}$Ne ages. The ages are in good agreement with the average age of 20±3 Myr for the Almahata ureilites [6]. Our results confirm the conclusion of others [2-5] that the Almahata chondrites are derived from the same meteoroid as the Almahata ureilites, and do not represent separate falls.

*Trapped Argon*. The trapped $^{36}$Ar contents of (5.4-23) x $10^{-8}$ cm$^3$ STP g$^{-1}$ are remarkably high for equilibrated ordinary chondrites, and do not appear to be due to atmospheric or solar wind Ar. Since the trapped Ar contents in the chondrites are in the lower end of the range of (13-1390) x $10^{-8}$ cm$^3$ STP g$^{-1}$ observed in the Almahata ureilites [6,13], it seems plausible that the trapped Ar component in #25 and A100 is ureilite-type Ar. This would suggest that either during the incorporation of the chondrites into asteroid 2008 $TC_3$ or slowly over time since incorporation, minor amounts of ureilitic material have been admixed into the chondrite fragments. If the trapped Ar component in the Almahata chondrite is indeed ureilitic, this observation provides additional evidence that the chondrites represent exotic inclusions in asteroid 2008 $TC_3$. Our conclusion is similar to the evidence that polycyclic aromatic hydrocarbons (PAH) with a ureilitic signature are found in some of the Almahata chondrites [14].

*Thermal history*. Using average U and Th concencentrations for chondrites, the radiogenic $^4$He concentrations of #25 and A100 yield identical U,Th-He ages of 3.8 Gyr for both samples. The fact that these two ages overlap may suggest that this age represents the time that the chondritic fragments were incorporated into the ureilitic parent body, which presumably involved a large catastrophic collision [2]. Given the U,Th-He age of ~3.8 Gyr, this event may be related to the Late Heavy Bombardment. The two chondrite samples show remarkably high $^{40}$Ar concentrations. Although the samples may contain a small contribution of trapped (atmospheric) argon, most of the $^{40}$Ar is probably radiogenic, yielding anomalously high K-Ar ages >4.5 Gyr.

**Conclusions:** The cosmogenic radionuclides in Almahata #25 and A100 indicate that both chondrites came from an object with a radius of ~300 g/cm$^2$, confirming the hypothesis that they represent exotic clasts from asteroid 2008 $TC_3$. The cosmogenic $^{21}$Ne/$^{26}$Al ratios yield CRE ages of 21 Myr (#25) and 23 Myr (A100), which overlap with the average $^{21}$Ne/$^{26}$Al age of 20±3 Myr for the Almahata Sitta ureilites [6]. The anomalously high trapped Ar component in the two chondrites is best explained by admixture of minor amounts of ureilitic host material to the enclosed chondritic lithologies, perhaps by a similar mechanism as suggested for the PAH's.

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**References**: [1] Jenniskens P. et al. (2009) *Nature, 458*, 485-488. [2] Bischoff A. et al. (2010) *MAPS, 45*, 1638-1656. [3] Shaddad M. H. et al. (2010) *MAPS, 45*, 1557-1589. [4] Kohout T. et al. (2010) *MAPS, 45*, 1778-1788. [5] Zolensky M. E. et al. (2010) *MAPS, 45*, 1618-1637. [6] Welten K. C. et al. (2010) *MAPS, 45*, 1728-1742. [7] Nishiizumi K. et al. (2007) *NIM, B258*, 403-413. [8] Nishiizumi K. (2004) *NIM, B223-224*, 388-392. [9] Sharma P. et al. (1990) *NIM*, *B52*, 410-415. [10] Wieler R. et al. (1989) *GCA, 53*, 1449-1459. [11] Eugster O. (1988) *GCA*, *52*, 1649-1662. [12] Leya I. and Masarik J. (2009) *MAPS, 44*, 1061-1086. [13] Ott U. et al. (2010) *LPSC XLI*, Abstract #1195. [14] Sabbah H. et al. (2010) *MAPS, 45*, 1710-1717.

Table 1. Concentrations of major elements (in wt%) and cosmogenic radionuclides (in dpm kg$^{-1}$) in the metal and stone fraction of two chondrites from the Almahata Sitta strewnfield. The last column represent neutron-capture $^{36}$Cl in the stone fraction.

| Sample | Mass | Mg | Al | Ca | Mn | Fe | Co | Ni | $^{10}$Be | $^{26}$Al | $^{36}$Cl | $^{36}Cl_{nc}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #25-metal | 77.2 | 0.013 | - | - | - | 88 | 0.43 | 10.3 | 2.92±0.10 | 2.37±0.12 | 14.4±0.4 | - |
| A100-metal | 44.3 | 0.076 | - | - | - | 85 | 0.68 | 12.2 | 3.99±0.10 | 3.38±0.20 | 19.4±0.5 | - |
| #25-stone | 133.0 | 17.8 | 1.13 | 1.42 | 0.28 | 13.6 | - | 0.17 | 20.2±0.6 | 66.7±2.9 | 8.1±0.2 | 2.3±0.8 |
| A100-stone | 123.5 | 16.5 | 1.19 | 1.07 | 0.26 | 16.1 | - | 0.32 | 21.8±0.7 | 68.7±2.6 | 10.5±0.2 | 3.9±0.9 |

Table 2. Concentrations (in $10^{-8}$ cm$^3$ STP/g) and isotopic ratios of He, Ne and Ar in two aliquots (of 65-183 mg) of two chondritic meteorites from the Almahata Sitta strewnfield. Columns labeled $^4He_r$ and $^{38}Ar_c$ give estimated concentrations of radiogenic $^4$He and cosmogenic $^{38}$Ar, respectively (see text).

| Sample | Mass | $^3$He | $^4$He | $^4He_r$ | $^{20}$Ne | $^{21}$Ne | $^{22}$Ne/$^{21}$Ne | $^{20}$Ne/$^{22}$Ne | $^3$He/$^{21}$Ne | $^{36}$Ar | $^{38}$Ar | $^{40}$Ar | $^{38}Ar_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #25-1 | 183.2 | 22.6 | 1495 | 1359 | 5.81 | 6.38 | 1.082 | 0.842 | 3.55 | 5.89 | - | 7480 | - |
| #25-2 | 67.8 | 23.5 | 1663 | 1522 | 6.03 | 6.63 | 1.078 | 0.845 | 3.54 | 8.45 | 2.54 | 7593 | 1.08 |
| A100-1 | 162.3 | 28.2 | 1821 | 1652 | 6.83 | 7.24 | 1.102 | 0.856 | 3.89 | 23.30 | 5.36 | 8094 | 1.12 |
| A100-2 | 65.8 | 31.4 | 1672 | 1483 | 7.79 | 8.22 | 1.098 | 0.863 | 3.81 | 21.57 | 5.08 | 7168 | 1.17 |